Metrology for Solid State Lighting

EURAMET
European Association of National Metrology Institutes

ENG05 Stakeholder Presentation

Colour Rendering Metrics

LNE
Le progrès, une passion à partager

Laboratoire national de métrologie et d'essais

ENG05 – Final meeting – Stakeholder presentation
April 25th – NPL Tedington

Colour Rendering Metrics of artificial light sources

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Metrology for Solid State Lighting

Colour Rendering Metrics

WP1: Traceability for SSL Measurements

WP2: Basic measurement methods for SSL characterization

WP3: Human perception of SSL

- **Task 3.1 : Colour rendering**
- **Task 3.2 : Visual comfort**
- **Task 3.3 : Mesopic vision for outdoor lighting**

WP4: Quality metrics for SSL characterisation

WP5: Creating impact

WP6: JRP Management and Coordination

Metrology for Solid State Lighting

Introduction to colour rendering

When objects are lighted by natural or artificial light sources their coloured appearance could change depending on the **spectrum of the light source** and the **reflectance spectrum of those objects.** Then depending on the light source a set of objects can appear with different degrees of perceptual colour properties/qualities (-ness) : naturalness, colourfulness, vividness, attractiveness, ….

The colour quality of a light source is usually specified by a single number the CIE **general colour rendering index CRI 13.3 R_a.** This index has a long history and was devised to assess the colour rendering of fluorescents lamps by comparison of a reference illuminant.

The **CIE does not recommend to use this index** to rank a set of light sources when this set comprises LED-based light sources. That follows many performed subjective experiments where the CRI failed to predict the subjective ranking. That gave rise to many proposals to supplement or complement the current rendering index. CIE **does not yet endorse new indices** and we do not know when a consensus will be reach ?

With the banning of no-efficient lighting sources and the deployment of SSL sources on the market there is a urgent need to develop and validate colours quality indices or metrics.

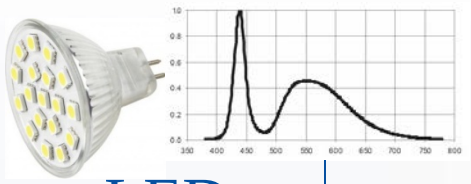
Introduction to the study on colour rendering metrics

The study on colour rendering was carried out following steps 1 to 6 for the ENG05 project, LNE will continue to work on steps 7 to 8. We present today the achieved steps (1->5) and the direction of the step in progress (6).

1. **reviewing and analysing all proposals of metrics,**
2. **implementing relevant metrics,**
3. **applying implemented metrics on a collection of SPDs,**
4. **performing a real life subjective experiment in a real size test room,**
5. **processing and comparing subjective ratings with metric's predictions,**
6. *complementing and/or supplementing current CIE CRI index with refined proposals for a better correlation with subjective scoring/ranking,*
7. *performing another subjective experiment for validation and further study,*
8. *Continuing the development for improved colour rendering metric.*

Colour Rendering: Reference-based approach implementation

Test ⟷ comparison ⟷ **Reference**



LED → CCT → CIE Daylight

5000 K

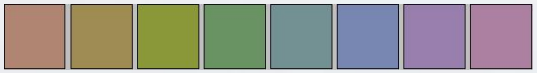
(x_T,y_T) → CAT ← (x_R,y_R)

Set of TCS

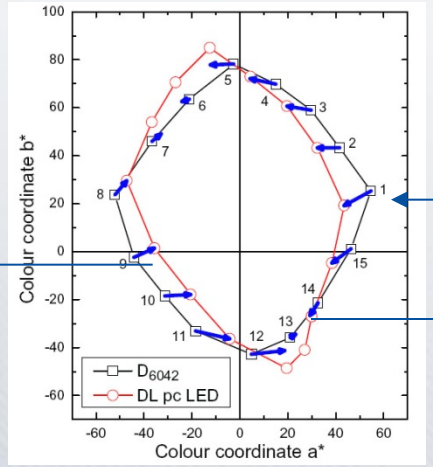
uniform colour space (a*,b*)

Planckian Radiator

Set of TCS



CAT



$\overline{\Delta E}$ ← |3D vector|

(CRV – L*a*b*)

Gamut (area)

(graph from Zukauskas – Colour rendition properties SSL paper)

Fidelity → **Quality Index** ← Vividness

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Assessment and improvement of Colour Rendering Metrics

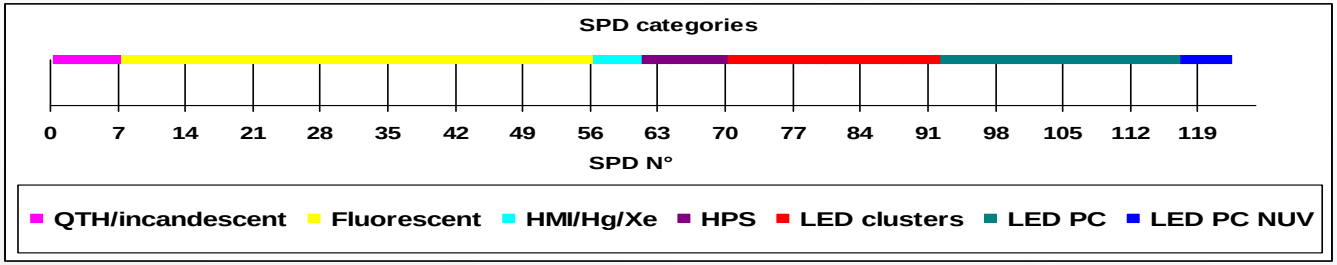
Review and implementation of proposals for a new metric

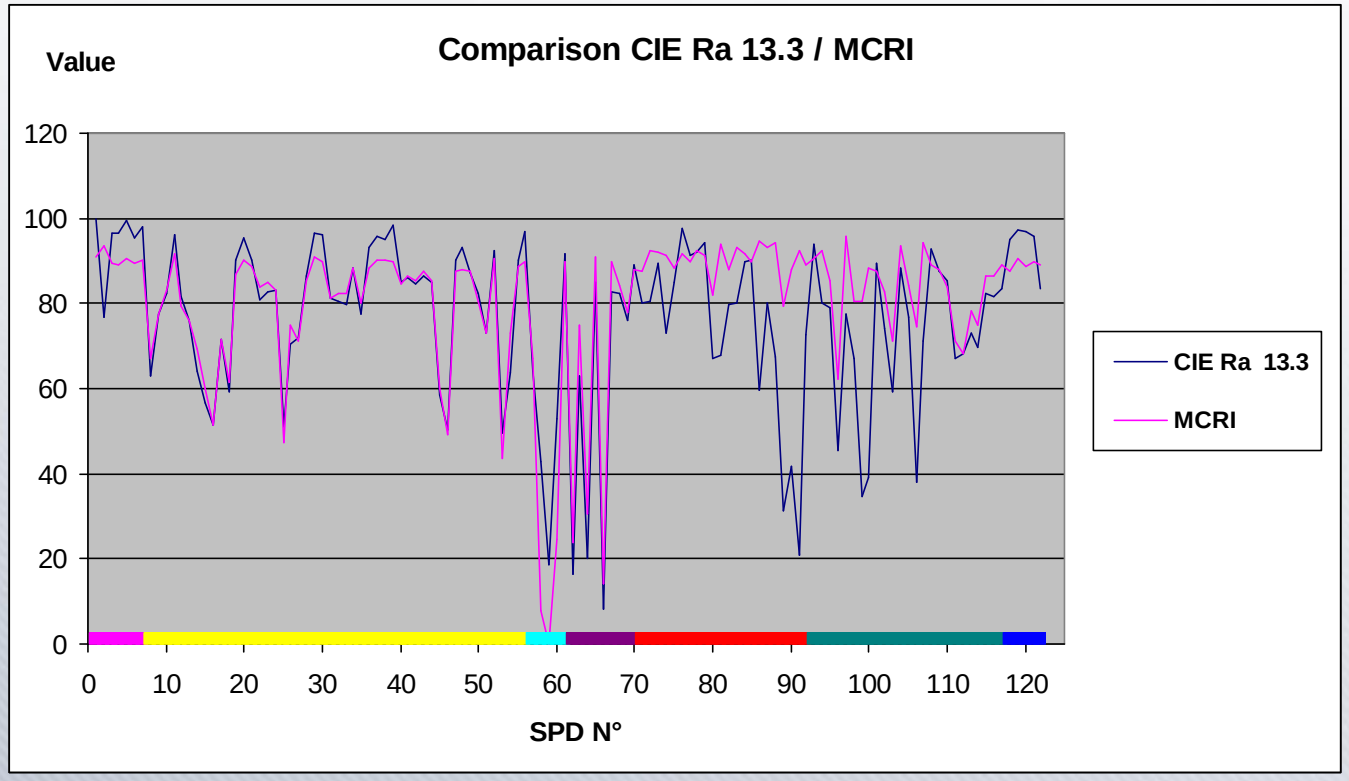
A large review of proposals for colour rendition metrics has been conducted, then the metrics have been sorted and implemented.

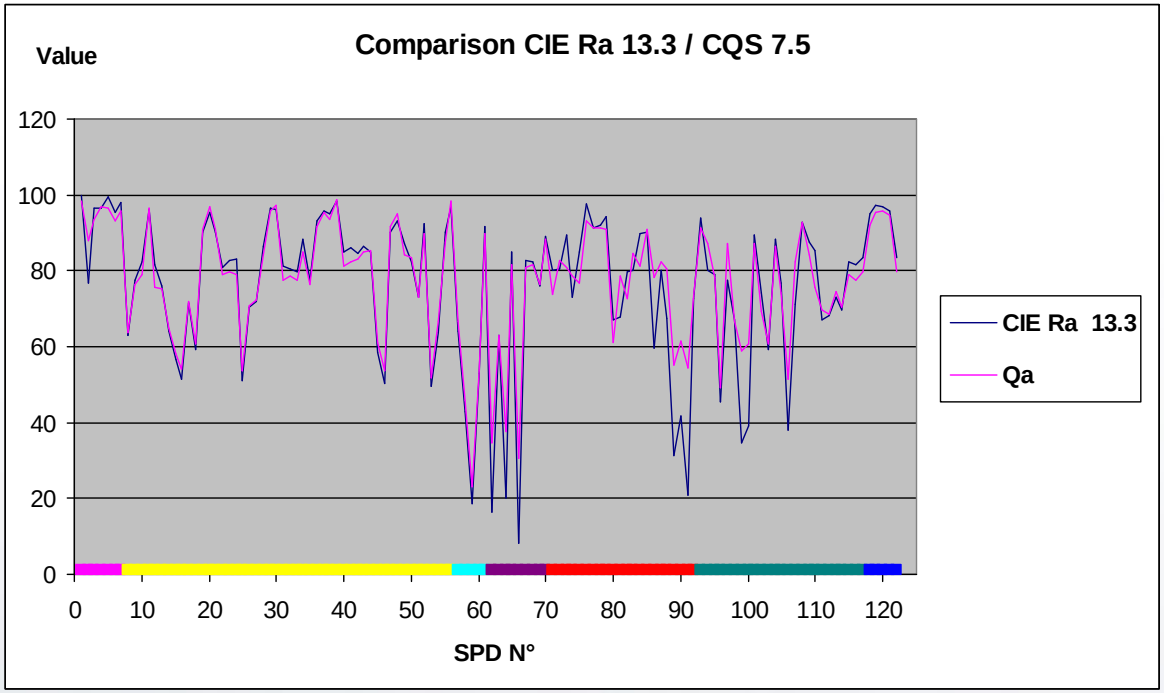
- **Reference source based methods (reference : daylight, Planckian radiator) – magnitude of colour shift between target and reference of same CCT and on a set of TCS** :
  - Fidelity based methods (CRI, CRI-CAMUCS update of CRI, RCRI ranking)
  - Non-fidelity based methods (CQS : discounts positive chroma shift)
  - Gamut based methods (GAI, GAS, FCI with luminance) – to supplement CRI, CQS – [could be also absolute gamut]
  - Statistical methods : colour categories CCRI, CRV, multidimensional criterion on fidelity, saturation , hue (counts on CRV tolerance)
  - Specific attribute based methods : colour harmony (HRI) / colour categories
- **Non-reference source based methods :**
  - Memory colours : similarity functions of memory colour objects (MCRI)
  - Miscellaneous : fidelity based but with modified TCS for reference (Flattery index)

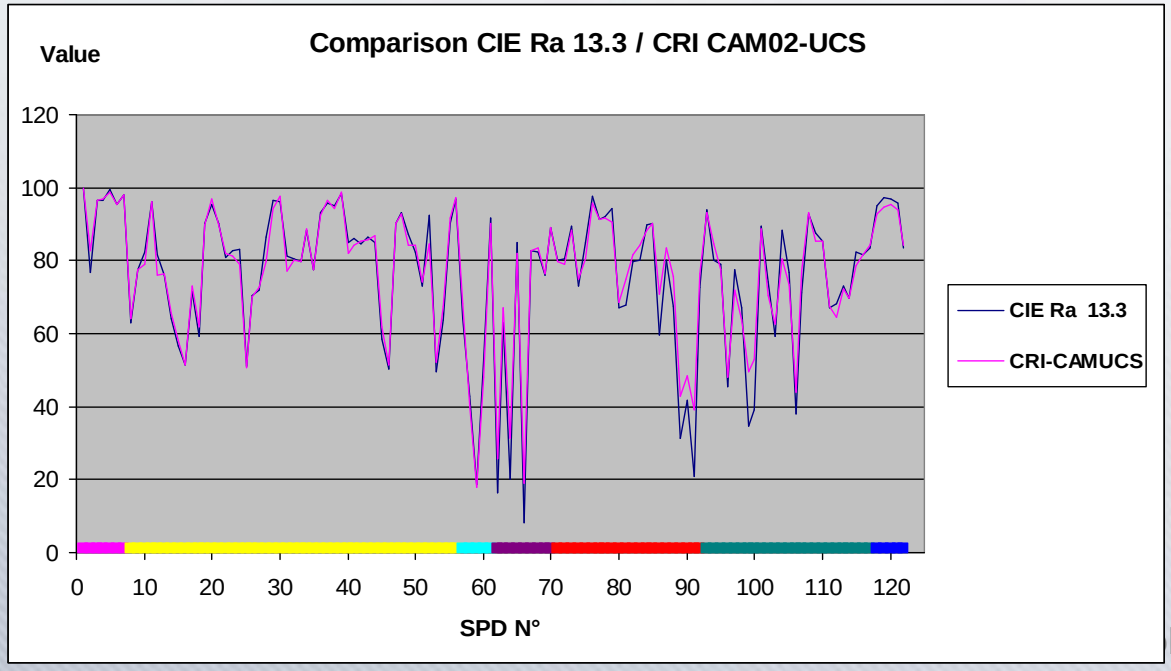
Review of proposals for a new metric : results on 122 SPDs

Application of the reviewed metrics on a set of 122 spectra of light sources representing all technologies.

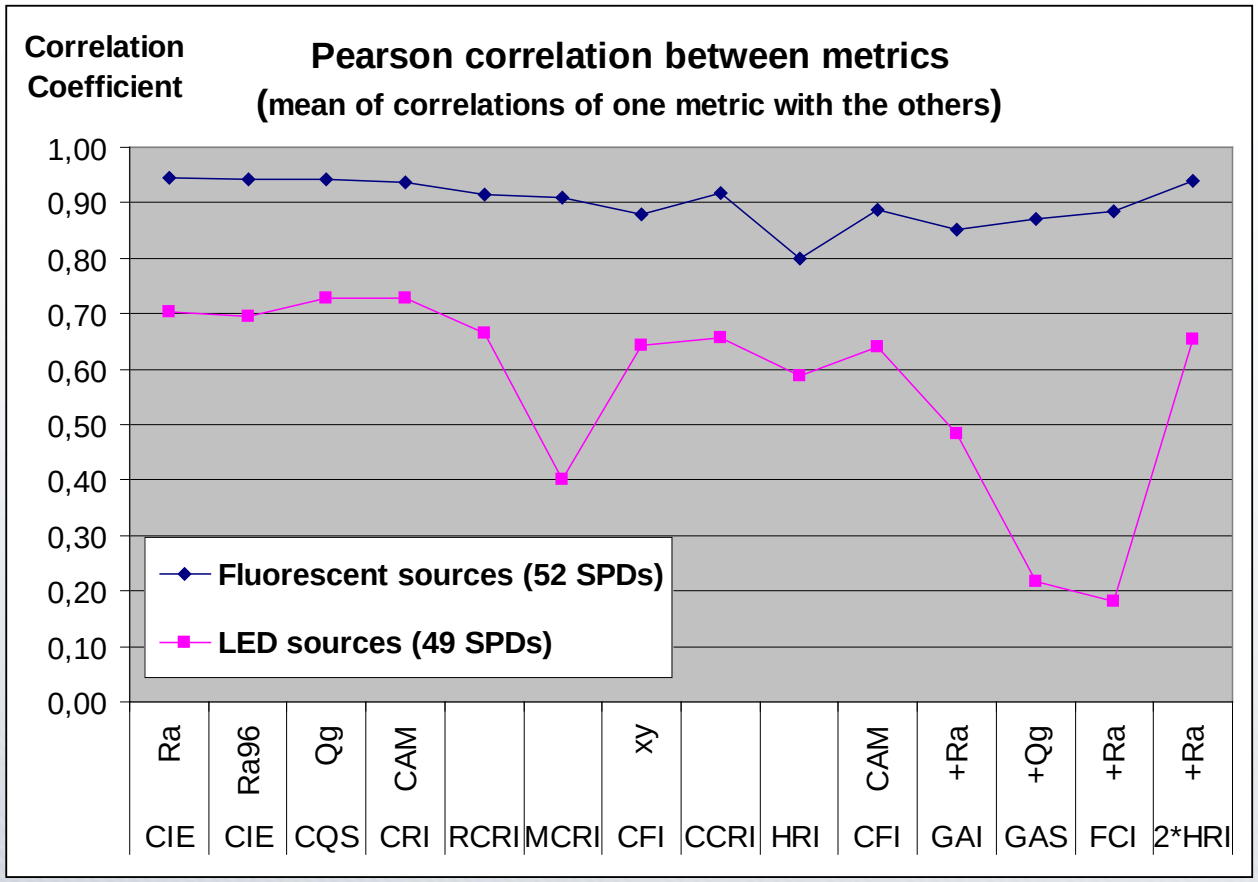





Comparison CIE Ra 13.3 / CQS 7.5
Value
120
100
80
60
40
20
0
0 10 20 30 40 50 60 70 80 90 100 110 120
SPD N°
CIE Ra 13.3
Qa


Comparison CIE Ra 13.3 / CRI CAM02-UCS
Value
120
100
80
60
40
20
0
0 10 20 30 40 50 60 70 80 90 100 110 120
SPD N°
CIE Ra 13.3
CRI-CAMUCS

Review of proposals for a new metric : results on 122 SPDs



Pearson correlation coefficients between metrics for the LED sources are quite low in comparison to those obtained with fluorescent sources demonstrating the special dimension of LED lighting.

Assessment and improvement of Colour Rendering Metrics
The subjective experiment : general

Objective of the experiment

To obtain from a panel of naïve observers the rating of **global preference** and detailed quality attributes --**without reference lighting source**-- in a common an versatile environment and with **all the common lighting technologies** (QTH, FL tubes, CFL, LED clusters, LED Phosphors Converted (blue/NUV LED).

Attributes to be judged (proposed definition) - 5 point-scale

- Global preference (observer's own criterion)
- Fidelity of colours (feeling of "true – false" colours)
- Quality of vividness (like – dislike)
- Naturalness: global, foliage, fruits/vegetables, skin (perceived degree of naturalness)
- Quality of the colour chart (colour discrimination, saturation, shading,…)

Panellist's data

43 Panellists: from 20 to 61 years old, 29 males / 14 females

Assessment and improvement of Colour Rendering Metrics
The test light sources : specification and main indices

- FL : fluorescent tube
- HAL : Quartz Tungsten Halogen
- CFL : compact fluorescent
- WW / CW : yellow phosphor and blue LED (warm white / cold white)
- WR : yellow phosphor and blue LED with a red LED
- NUV : RGB phosphors – NUV LED (**Mitsubishi Chemical**)
- RGB / RGBY : LED clusters

	CCT (K)	CIE Ra	CQS Qa	MCRI Sa	CRICAM UCS	RCRI
FL 5000K	4745	93,7	96,45	92,28	94,3	100
LED NUV 5000K	5024	98,1	99,1	90,73	98,51	100
LED CW 5000K	5481	70,68	71,33	75,71	71,02	56,09
LED RGB 5000K	5293	35,58	62,89	94,53	49,72	56,09
LED WR 2700K	2906	88,56	90,48	91,15	86,79	98
CFL 2700K	2708	82	75,78	77,87	75,97	74,4
RGBY 2700K	2781	76,2	79,06	89,98	80,27	80,9
HAL 2700K	2739	99,7	96,91	89,38	99,02	100
LED WW 2700	2624	82,78	79,4	85,16	78,82	74,4

Average illuminance
350 lux (+-10%)

Assessment and improvement of Colour Rendering Metrics
The subjective experiment : procedure

- Test presentation to observer (written text).
- Vision test : 15 Farnsworth Munsell desaturated panel.
- Training section with 4 different lights (2 times).
- Rating of 2 sequences of the 9 lights sources (~1hour)

  (for each individual 2 orders out of 9 different orders). Examples of orders:

	order A	order B	order C
1	HAL 2700K	RGBY 2700K	CFL 2700K
2	CFL 2700K	CFL 2700K	LED WR 2700K
3	LED WW 2700	LED WW 2700	LED WW 2700
4	LED WR 2700K	HAL 2700K	RGBY 2700K
5	RGBY 2700K	LED WR 2700K	HAL 2700K
6	FL 5000K	LED CW 5000K	LED RGB 5000K
7	LED NUV 5000K	FL 5000K	LED NUV 5000K
8	LED RGB 5000K	LED RGB 5000K	LED CW 5000K
9	LED CW 5000K	LED NUV 5000K	FL 5000K

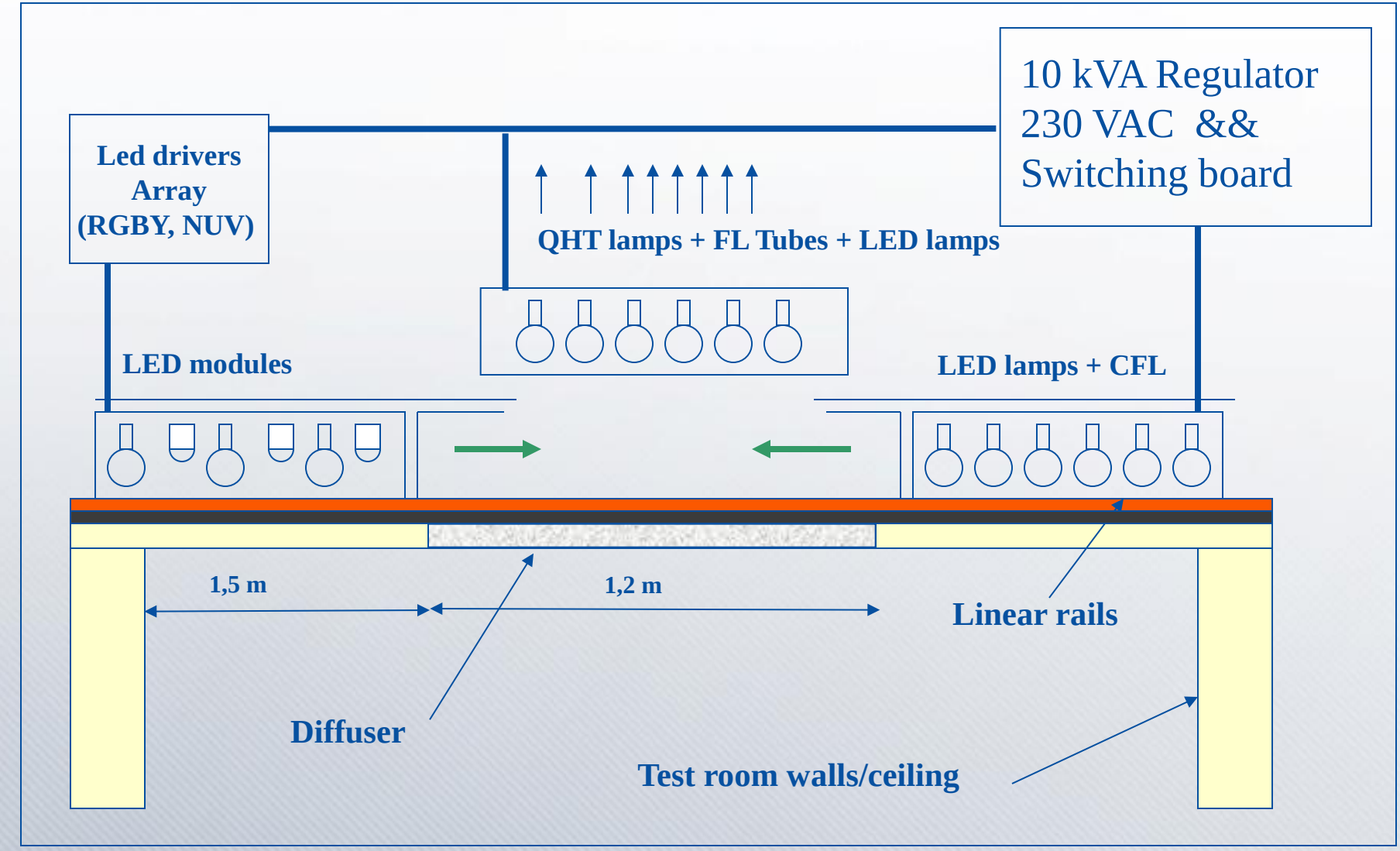
Assessment and improvement of Colour Rendering Metrics

The subjective experiment : test room

Light panel: lamps behind a diffuser and attached to 3 frames

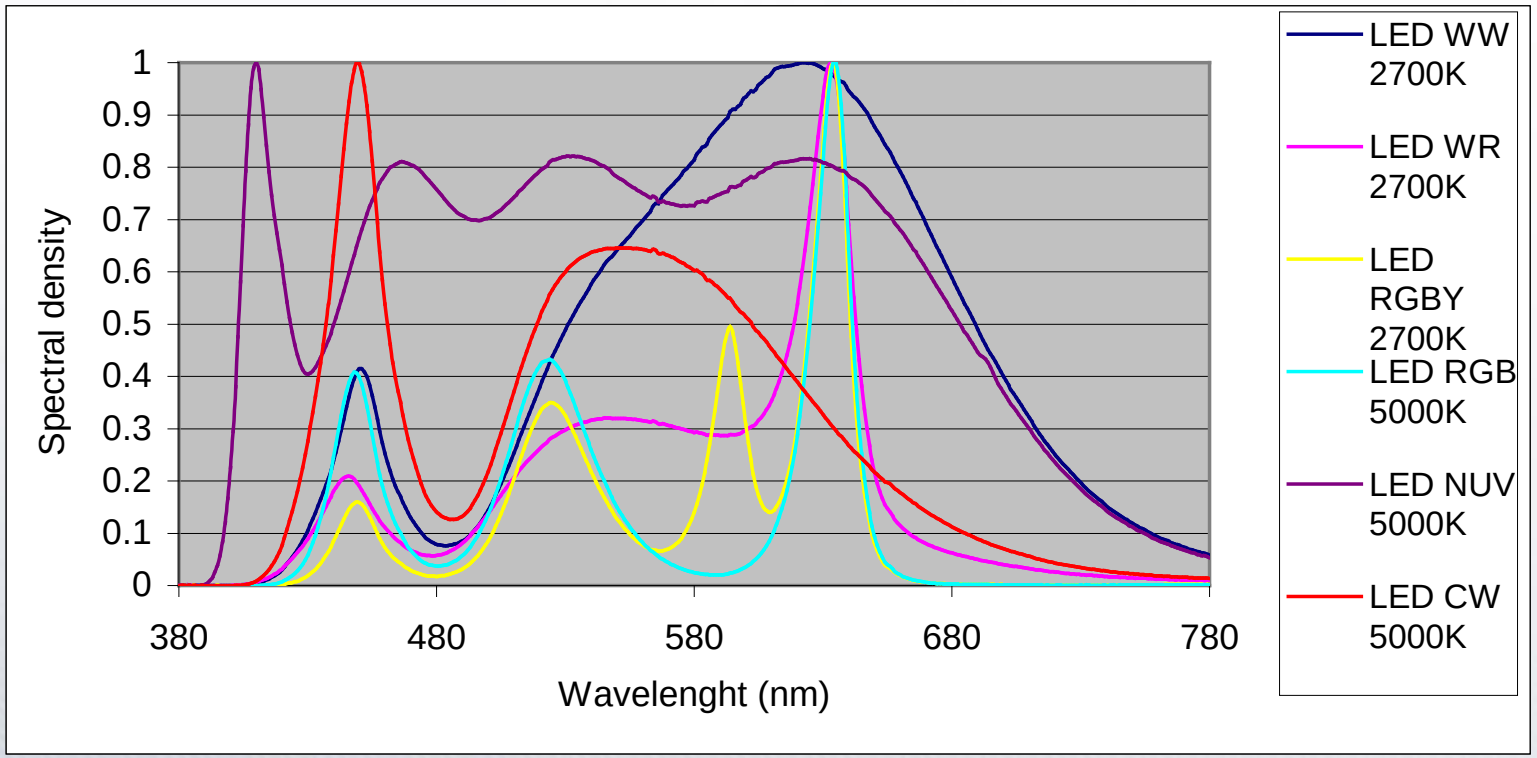
Assessment and improvement of Colour Rendering Metrics

The subjective experiment : test room 4 x 4.5 m²



Assessment and improvement of Colour Rendering Metrics

The subjective experiment : test SPDs



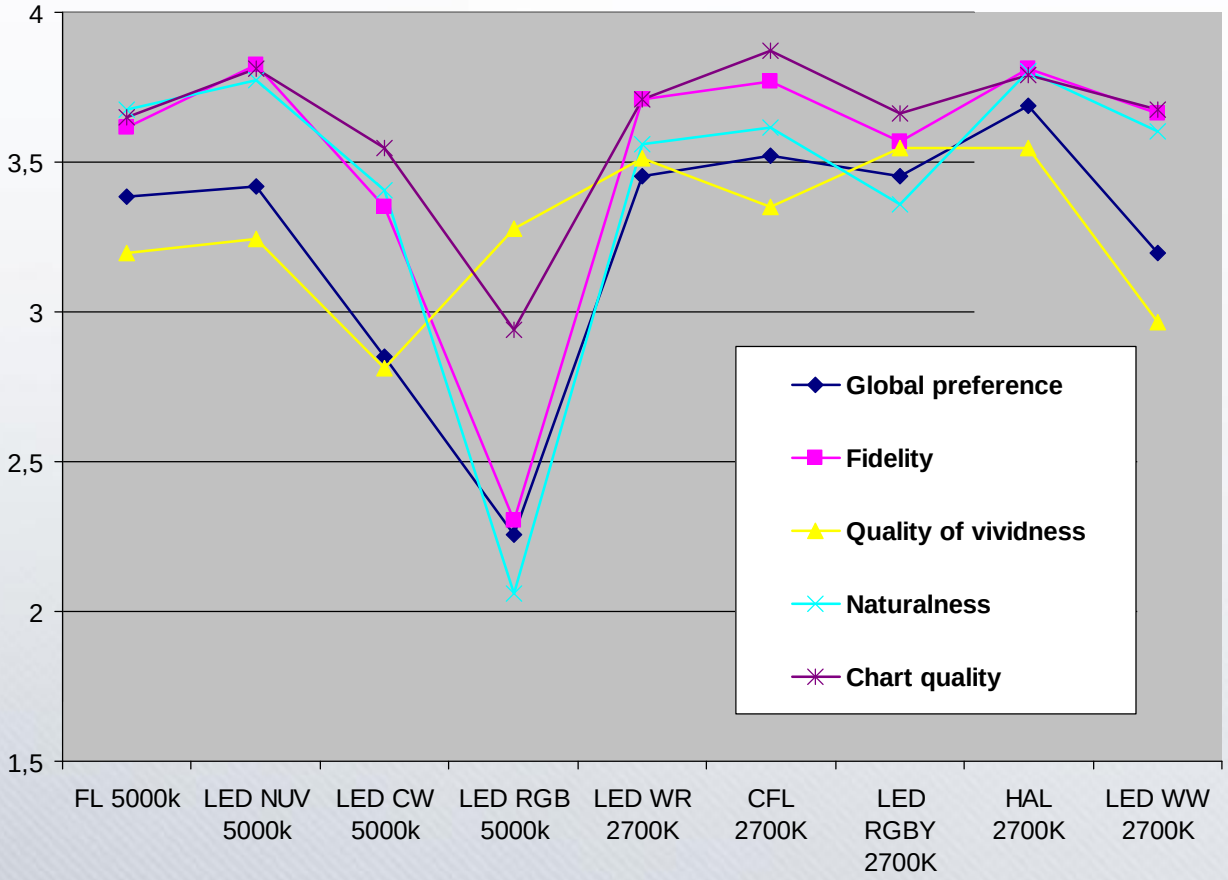
SPD of LED light sources used in the experiment

Assessment and improvement of Colour Rendering Metrics

Fruits and vegetables appearance under the test light sources

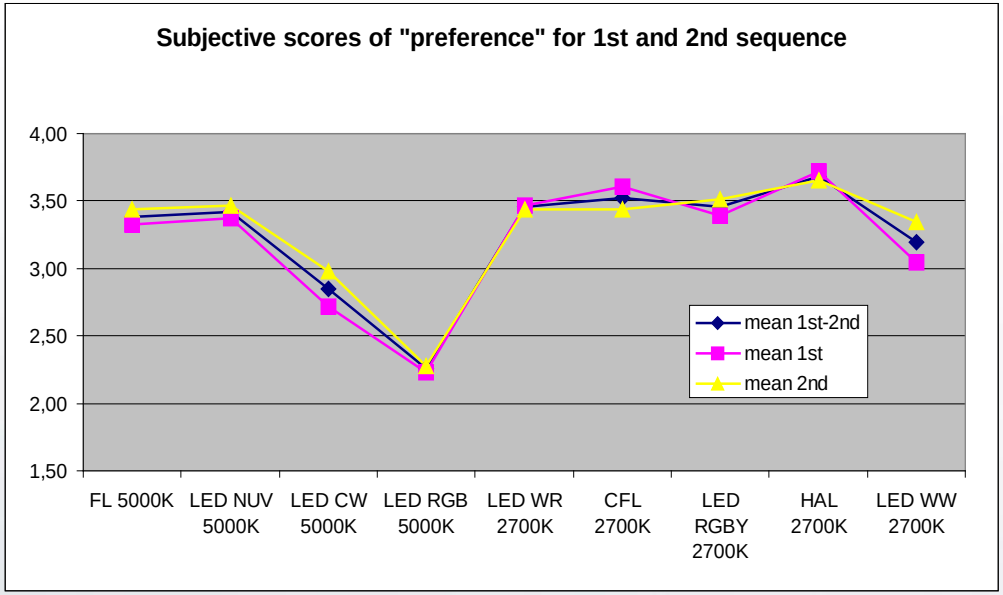
Assessment and improvement of Colour Rendering Metrics

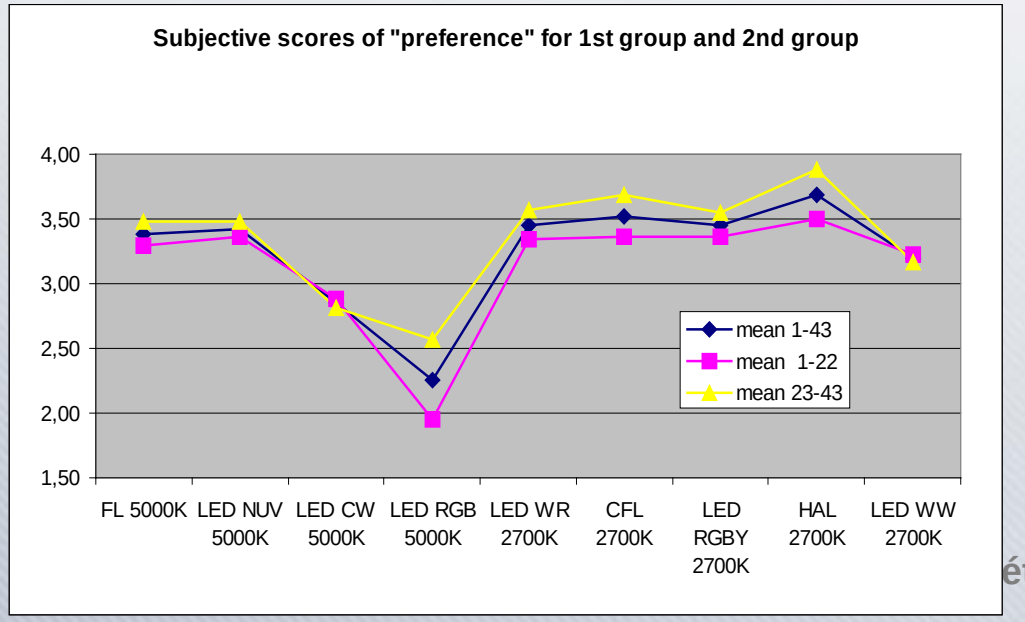
Average scores of the quality attributes



The analysis and processing of subjective data are in progress. The first result of the PCA is that all attributes are represented with the first principal component (factor 1) at a level of 66 % (% of total variability) and in the same direction.

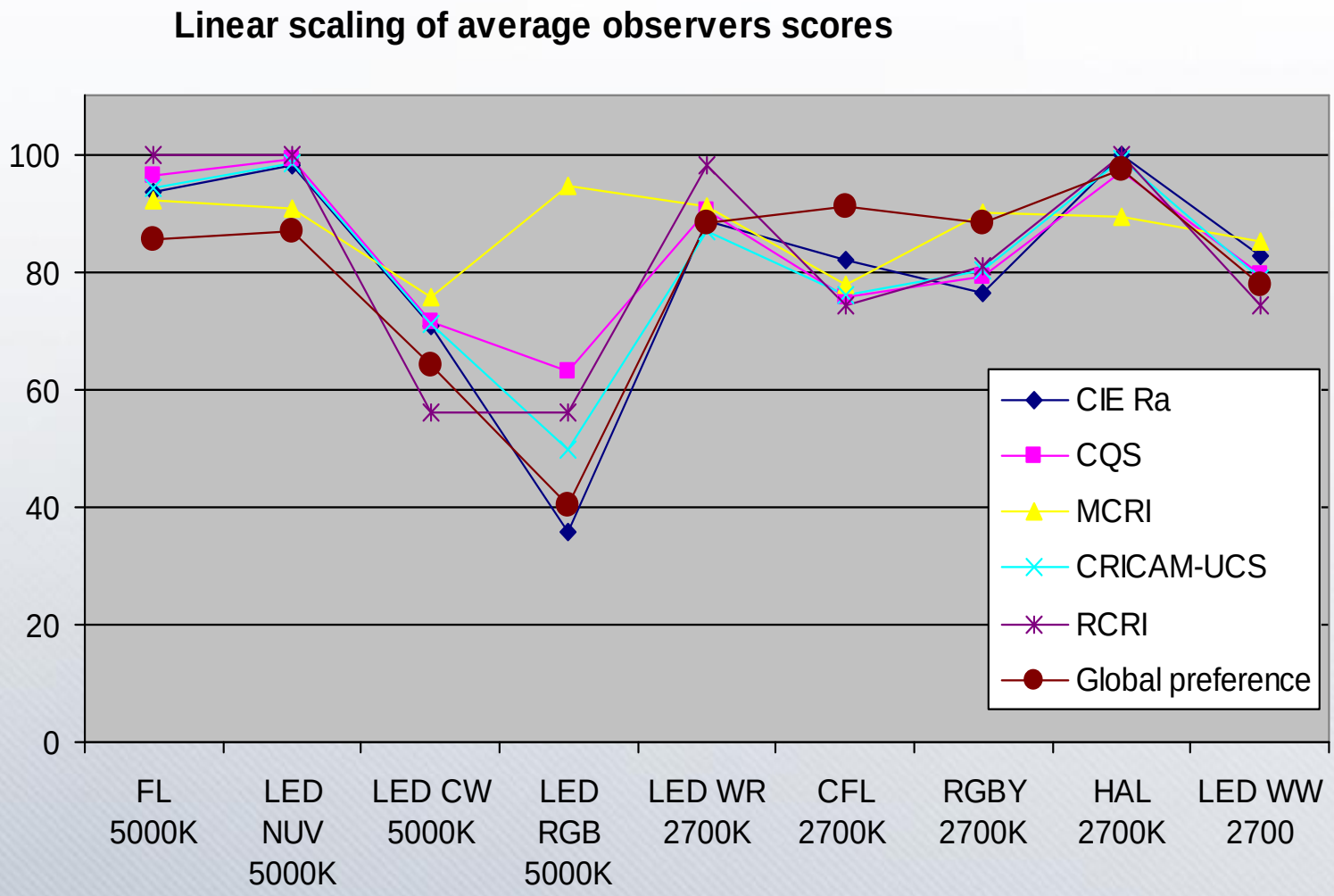
Assessment and improvement of Colour Rendering Metrics
Analysis of subjective rating of the preference attribute





Assessment and improvement of Colour Rendering Metrics

Comparison of metric predictions with subjective preference



Comparison of predictions with subjective preference : correlations

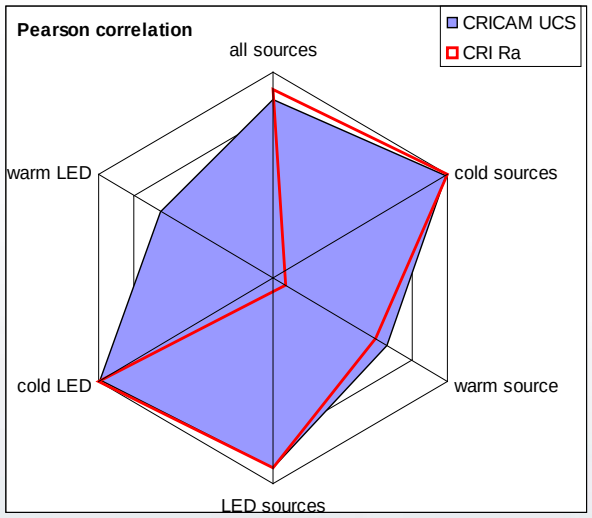
The following tables are the Pearson (linear) and Spearman (rank) coefficients of correlation of metrics with the subjective rating of preference – [scores are rounded at +/- 1%].

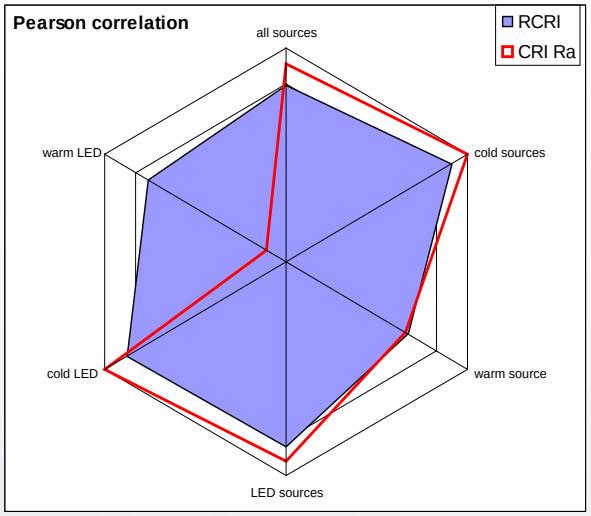
Pearson	CIE Ra	CQS Qg	MCRI	CRI CAMUCS	RCRI
all light sources	0,918	0,778	-0,028	0,868	0,788
cold lights	0,997	0,968	-0,022	0,996	0,895
warm lights	0,666	0,606	0,136	0,738	0,648
all LED sources	0,921	0,847	0,026	0,913	0,829
all cold LED	1,000	0,958	-0,236	0,997	0,853
all warm LED	0,000	0,500	0,945	0,693	0,693

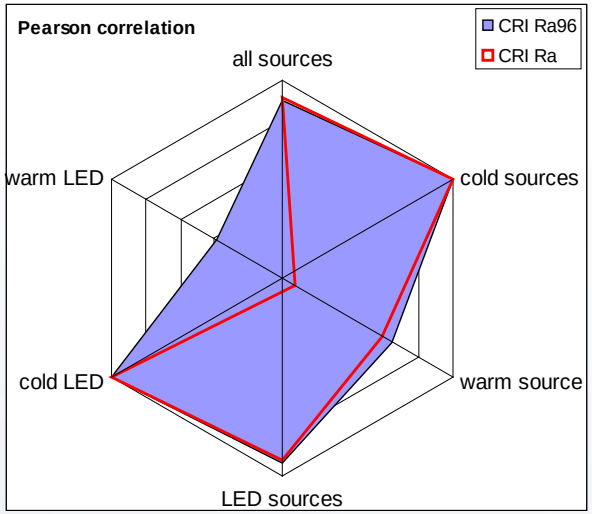
Spearman	CIE Ra	CQS Qg	MCRI	CRI CAMUCS	RCRI
all light sources	0,616	0,466	-0,112	0,605	0,538
cold lights	0,949	0,949	-0,316	0,949	0,943
warm lights	0,526	0,289	-0,026	0,359	0,526
all LED sources	0,667	0,750	0,074	0,812	0,794
all cold LED	1,000	1,000	-0,500	1,000	0,866
all warm LED	0,000	0,500	0,866	0,866	0,866

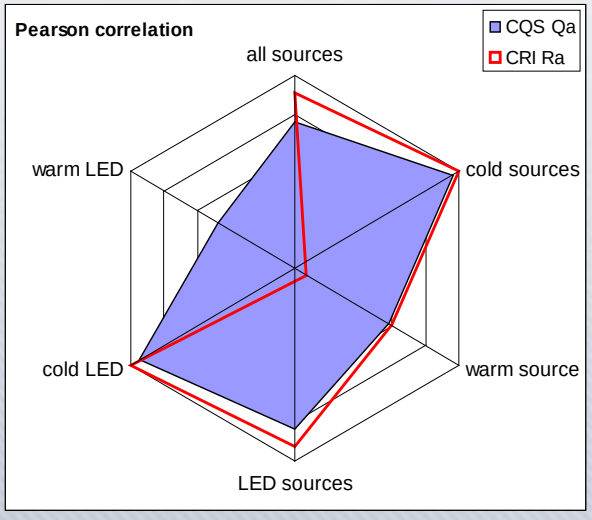
These results show that there is a difference of metrics correlation between warm light sources and cold light sources. While current CRI Ra fails for warm LEDs, proposals better perform but exhibit lower correlation for cold light sources – Better correlation calculation and more samples by categories are needed to give better statements.

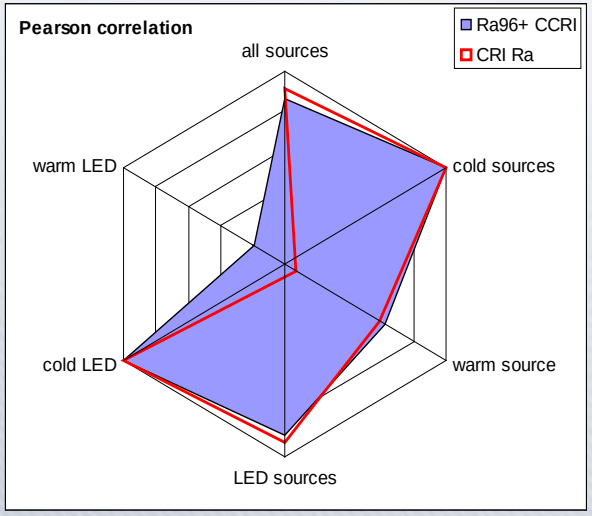
Comparison of predictions with subjective preference : correlations

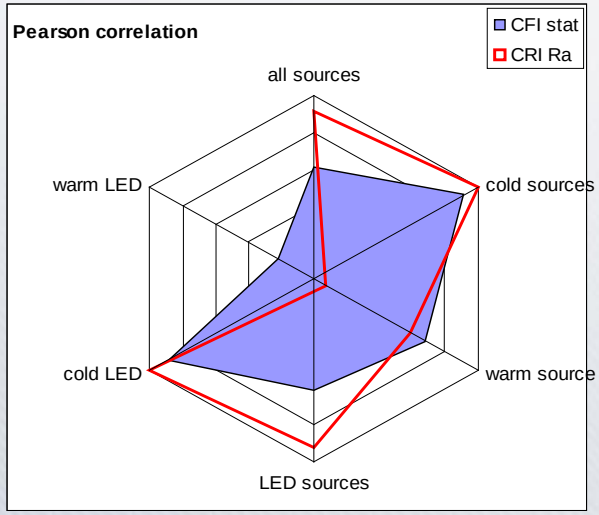












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Assessment and improvement of Colour Rendering Metrics

Conclusion

- Differences in dimensions of colour rendering (fidelity, preference), in approach of proposals, in predictions, and in assessments with subjective experiments show that a good deal of work is needed to validate metric and reach consensus.
- All the metrics rewarding the increase of chroma, or working with augmented chroma for reference rank better warm LED lighting sources, but the conducted subjective experiment also shows that new metrics for warm lightings do not improve too much the ranking with mixed technologies (halogen, CFL, LED).
- One other outcome of the experiment is that for low gamut/low quality (low CCT) enhancement such as chroma increase (LED lighting property), is preferred but for higher gamut/quality (high CCT) increase of saturation has no effect or is not desirable. We will propose a metric based on this principle.

Assessment and improvement of Colour Rendering Metrics
Conclusion

- Industries will not adopt a metric not endorsed by CIE, and CIE will not adopt metrics not thoroughly tested by subjective experiments. Among metrics under consideration at the CIE TC1-69 there are the CQS and the nCRI - nCRI is based on CRI-CAM02US with a larger set of TCS, selected with regards to low and high colour constancy, and with scaling methos similar to CQS.
- The subjective experiment and the research conducted in this study address the consumer's preference, other work should be conducted for other environments like "office lighting" where requirements are different : colour fidelity for the colour constancy of objects (prints, paints, textile, materials), stimulating environment for productivity,…

Special acknowledgement to Mitsubishi Chemical for the gift of several rolls of CMS NUV LED , to Y. Ohno and K. Smet for sending their Excel Spreadsheets implementing CQS and MCRI.

Thank you for your attention !

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